Soils and Foundations 2012;52(5):956–974

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

Building damage associated with geotechnical problems in the 2011 Tohoku Pacific Earthquake

Kohji Tokimatsu[a,*], Shuji Tamura[b], Hiroko Suzuki[a], Kota Katsumata[a]

[a]*Department of Architecture and Building Engineering, Tokyo Institute of Technology, Japan*
[b]*Disaster Prevention Research Institute, Kyoto University, Japan*

Received 31 October 2011; received in revised form 4 April 2012; accepted 1 May 2012
Available online 20 December 2012

Abstract

An overview of the geotechnical aspects of the building damage due to the 2011 Tohoku Pacific Earthquake is presented, based on field reconnaissance made after the earthquake. It is shown that (1) Extensive soil liquefaction occurred along the coast of Tokyo Bay and around the floodplain of the Tonegawa River. Liquefaction was primarily found within the relatively newly reclaimed area, with numerous sand boils and large ground settlements up to 60 cm, accompanied by the settlement/tilting of wooden and reinforced concrete buildings supported by spread foundations. The extent and the distribution of the damage were significantly affected by the local soil conditions, including the thickness and the age of the reclaimed fills, the depth to the bedrock or the natural site period, and whether remedial measures had been taken against soil liquefaction, as well as the effects of structure–soil–structure interaction. (2) Numerous houses in Sendai's hilly residential areas constructed with the cut-and fill method were badly damaged not only by the simple collapse of retaining walls, but also by slope failures in the fills. It was found that most of the slope failures occurred on earth fills. (3) Several pile-supported buildings tilted and settled not only in the Tohoku region, but also on the Kanto plain, implying damage to pile foundations. Ground subsidence with sand boils around those buildings suggests that soil liquefaction might have played a significant role in intensifying the damage. (4) Within Onagawa and Rikuzen-Takata, several steel and reinforced concrete structures were knocked over by tsunami surges, probably after having suffered damage to their pile foundations. Much of the pile damage was concentrated (a) at the joints between pile caps and the piles themselves and (b) near the pile heads. The buildings suffering such damage were old; apparently their pile foundations were not designed to withstand earthquakes.

Keywords: The 2011 Tohoku Pacific Earthquake; Foundation; Ground subsidence; Landslide; Soil liquefaction; (IGC: E08)

1. Introduction

A massive earthquake shook northeastern Japan at 2:46 p.m. on March 11, 2011. With a magnitude of 9.0, The Tohoku Pacific Earthquake, centered off the Sanriku Coast, caused the strongest motion ever recorded in Japan. The earthquake triggered a giant tsunami, which caused huge damage mainly in the Tohoku region and left about 20,000 people dead or missing.

The earthquake and tsunami also triggered a nuclear crisis at the Fukushima Daiichi Nuclear Power Plant of Tokyo Electric Power Co., with unfathomable consequences. Furthermore, soil liquefaction and other ground failures caused extensive damage to infrastructures, lifelines, houses and other structures (Architectural Institute of Japan, 2011).

*Corresponding author.
E-mail address: kohji@o.cc.titech.ac.jp (K. Tokimatsu).
Peer review under responsibility of The Japanese Geotechnical Society.

Production and hosting by Elsevier

0038-0806
http://dx.doi.org/10.1016/j.sandf.2012.11.014

A group of researchers, including the authors of this study, carried out a field survey starting on March 12. Focus was placed on geotechnical problems, the damage to structure foundations and the ground behavior near the K-NET (Kyoshin strong motion network) strong motion stations in the following areas: In the Kanto region, along the coast of Tokyo Bay (Yokohama City and Shinkiba, and Urayasu and Makuhari) and the Tone River Basin (Abiko, Katori, Itako and Kamisu Cities) and Hitachinaka City, and in the Tohoku region, Sendai City and the Sanriku Coast (from Onagawa to Rikuzentakata) (Tokimatsu et al., 2011).

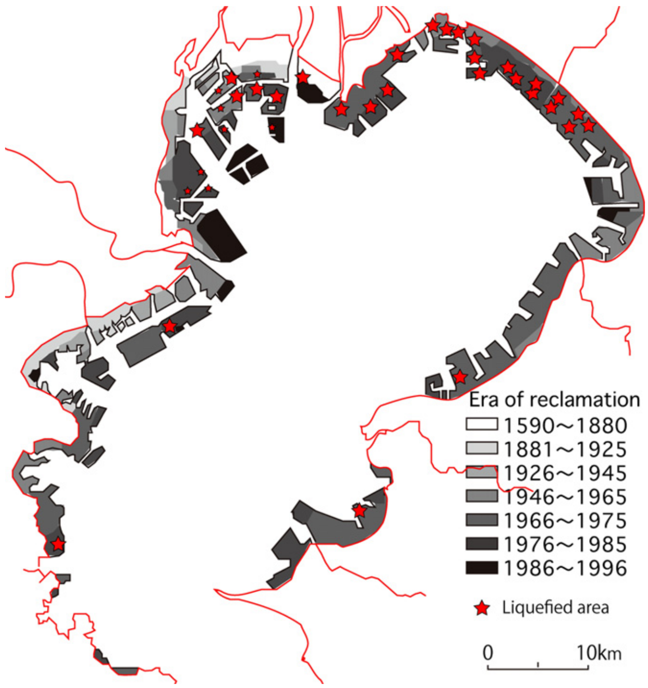

Fig. 1. Map showing reclaimed areas and periods together with liquefied areas.

This paper reports on the results of the survey. It is important to note that a survey by individual researchers can cover only a small portion of the vast stretches of land affected by the disaster. Furthermore, surveys on the reaches of the Tone River and the Tohoku region were conducted after mid-March and early April, respectively. This paper, therefore, may not necessarily present the entire picture of the damage. The findings reflect how things were at the time of the surveys, including the effects of the aftershocks.

2. Soil liquefaction damage in Tokyo Bay waterfront areas

2.1. Ground characteristics of liquefaction sites and seismic motions

Fig. 1 shows correlations between the reclaimed areas (and years of reclamation work) and the sites where soil

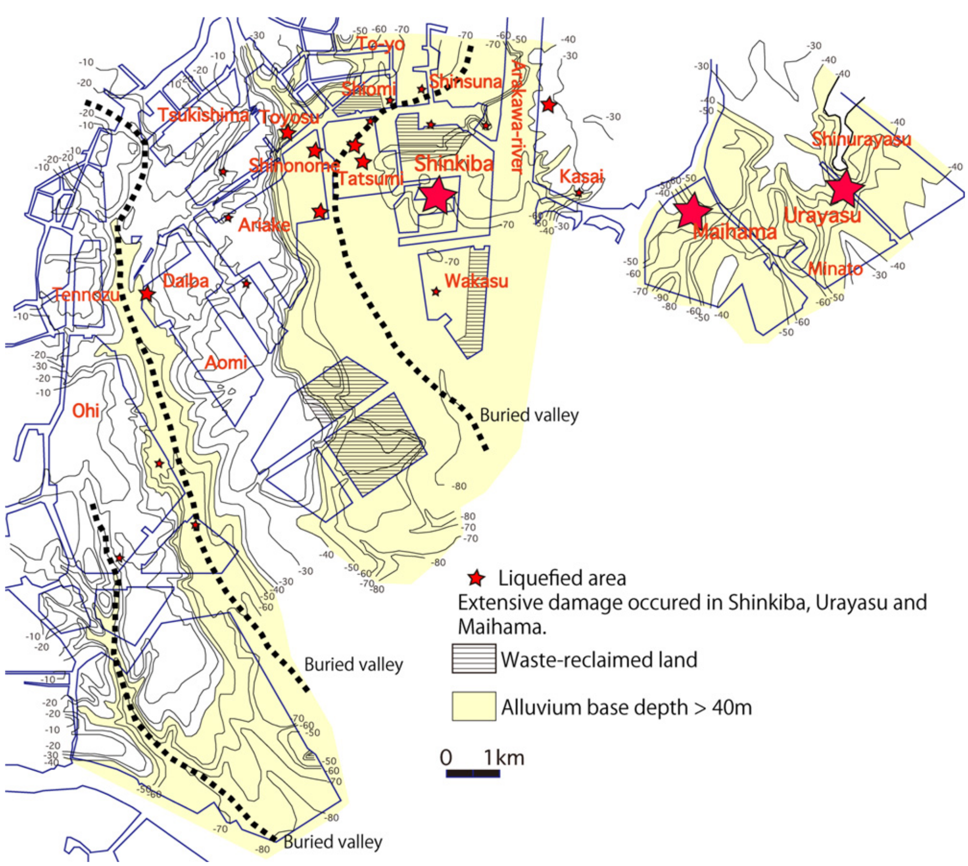

Fig. 2. Map showing depth of alluvial deposit and liquefied area.

liquefaction was observed (Kaizuka, 1993). The figure clearly indicates that liquefaction occurred only in the reclaimed land areas. Fig. 2 shows correlations between the depth of the alluvial basement and the liquefaction sites (Bureau of Port and Harbor, Tokyo Metropolitan Government, 2001; Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transportation and Tourism, 2011; Ministry of Land, Infrastructure, Transportation and Tourism, 2011). It is interesting to note that most of the extensively liquefied sites are located in areas where the basement depth is 35–40 m or more.

Among the K-NET strong motion stations along the coast of Tokyo Bay, at which digitized time-history data of the main shock are available (National Research Institute for Earth Science and Disaster Prevention, 2011), soil liquefaction was observed near two stations, namely, at K-NET Inage (CHB024) and at K-NET Tatsumi (TKY017). No liquefaction was spotted in the neighborhood of K-NET Urayasu (CHB008), which is located north of the old coastline in Urayasu City.

The acceleration time history at K-NET Inage (a duration of 100 s including principal motions) is shown in Fig. 3. The peak acceleration was 2.34 m/s^2 in the north–south direction and 2.03 m/s^2 in the east–west direction. Spiky waves, occurring for around 120 s, suggest the possibility of the cyclic mobility of sand in the liquefaction process. Fig. 4 shows the running spectrum at K-NET Inage, normalized at the spectral peak of each 10-second interval. The periods become elongated from 0.7 s to about 4 s between 110 s and 140 s. This suggests that the ground liquefied gradually with cyclic loading during the 30 s. Figs. 5 and 6 present similar data for K-NET Urayasu, where no liquefaction occurred. Unlike that at K-NET Inage, the running spectrum at K-NET

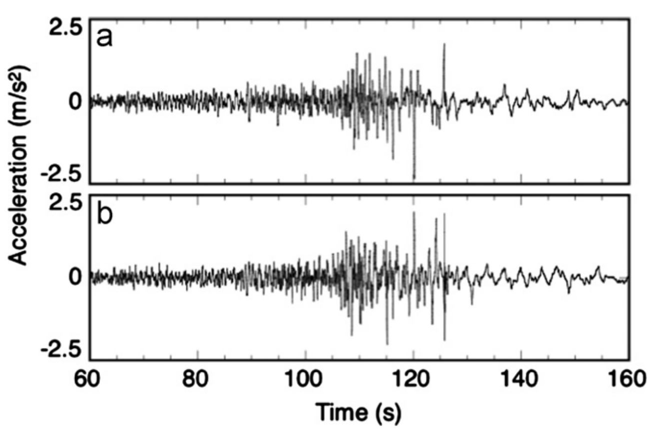

Fig. 3. Acceleration time histories at K-NET Inage during main shock.

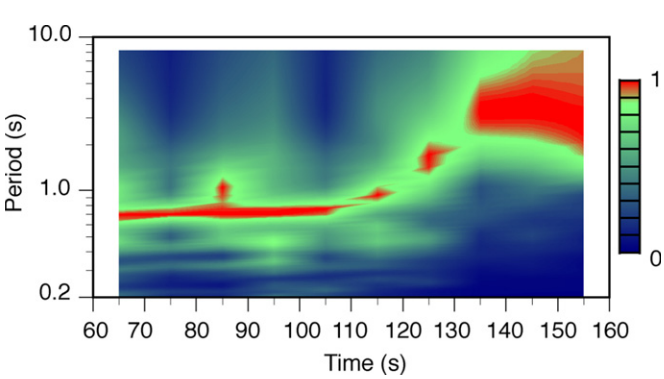

Fig. 4. Normalized running spectra in Inage.

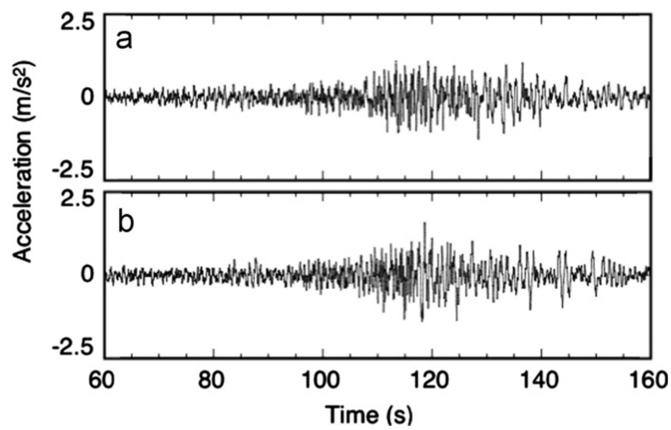

Fig. 5. Acceleration time histories at K-NET Urayasu during main shock.

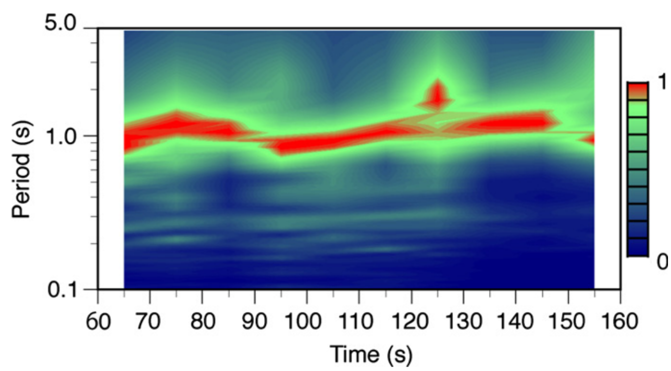

Fig. 6. Normalized running spectra in Urayasu.

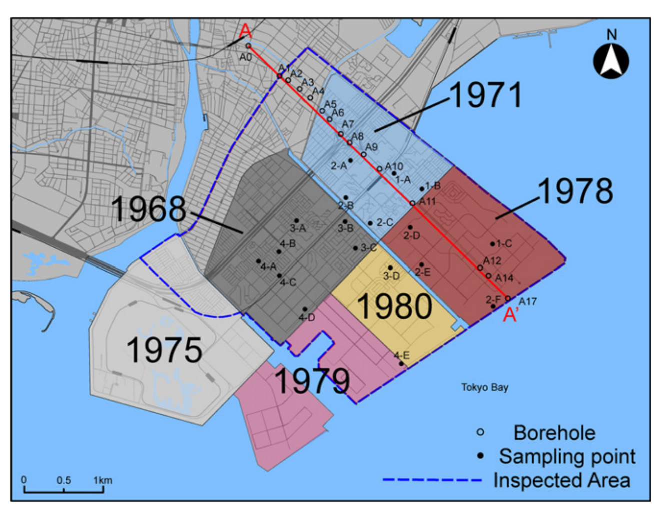

Fig. 7. Map showing reclaimed period and investigated area.

Urayasu shows no apparent changes in the spectral peak period. Considering the fact that the principal motion with accelerations greater than about 1 m/s^2, at the non-liquefied Urayasu site, lasted about 30 s from 110 to 140 s, complete liquefaction in Inage is likely to have occurred in the latter part of the principal motion.

2.2. *Soil liquefaction damage in Urayasu City*

Extensive soil liquefaction occurred in a reclaimed area along the coast of Tokyo Bay, including Shinkiba in Koto Ward, Urayasu City, Ichikawa City, Funabashi City, Narashino City, and Mihama Ward in Chiba City (Koto Ward, 2011; Chibaken Kankyo Kenkyu Center, 2011). This section reports liquefaction damage in Urayasu City, Chiba Prefecture.

Fig. 7 shows a map of Urayasu City, Chiba Prefecture, which was covered by this survey, and the years when reclamation work was done for each area (Urayasu City: Project of reclaimed land, 2011). The work in this area was started around 1964 outside levees along the old coastline. Many houses, commercial buildings and public facilities were built in the areas reclaimed during the first phase of the project ending in 1975. Meanwhile, many high-rise condominium buildings, universities, hotels and storehouses were built in the areas completed during the second phase ending in 1980. Vacant lots still dot areas near the coast. Sand excavated from the seabed off Urayasu was mainly used to fill the reclamation sites. In Urayasu City, a magnitude-6.7 earthquake, that occurred off Eastern Chiba Prefecture on Dec. 17, 1987 (Chibaken Toho-oki Earthquake), reportedly caused liquefaction in such

areas as Kairaku 1-chome, Mihama 3-chome and Irifune 4-chome.

The authors' group carried out a survey in the area circled by the dotted line in Fig. 7. In the survey area, no liquefaction damage was observed northwest of the old coastline, including the neighborhood of Urayasu Station and the K-NET Urayasu site. The survey made the following findings that are common to the areas covered:

- In many areas where no liquefaction occurred, including Tokyo Disneyland, ground improvement work of some kind had been carried out. This confirms the effectiveness of ground improvement work against earthquake shaking with a peak ground acceleration of 2.0 m/s^2 caused by the magnitude-9.0 earthquake.
- In areas where liquefaction did occur, many sand boils (Photo 1), ground settlements as well as the settlements

Photo 1. Boiled sand stacked on road.

Photo 2. Large settlement of building.

Photo 3. Largely tilted building.

Photo 4. Pile-supported building and settled building.

and tilting of buildings and houses on spread foundations (Photos 2–4) were observed, and gaps were created between pile-supported structures and the surrounding ground (Photos 4 and 5), causing damage to piping and other facilities. Underground facilities, such as manholes, emergency water tanks and parking lots were uplifted (Photos 6 and 7), tap water and sewerage systems were damaged, roads had dents and utility poles were toppled. However, little or no damage to superstructures, induced by the seismic forces, was observed.

- Even where foundations settled or tilted, few upper structures suffered damage as a result. This is because many buildings had adopted mat foundations or highly rigid foundations to prevent damage from liquefaction or uneven settlings.
- RC houses, and houses whose first floor or semi-basement was made of reinforced concrete to prevent flood damage, suffered relatively heavy settlement. This is probably because their ground contact pressure was greater.
- When two buildings stood closely together, they often tilted toward each other, as in Photo 3. This is supposed to have occurred because the ground settlement between the two structures is greater due to their combined weight load. When buildings faced each other across a street, they tended to tilt backward, away from each other, as in Photo 1. The reason is supposed to have been their proximity to other buildings behind them, which made them tilt toward those closer buildings.
- Several pile foundations, including some under construction during the main shock, reportedly suffered severe damage.

Photo 5. Ground settlement around pile-supported building.

Photo 6. Uplift of manhole.

Photo 7. Uplift of underground parking lot.

Based on the field performance of soils and buildings, including ground settlements as well as the settlements and tilting of houses, the authors have created a damage map on which the extent of the soil liquefaction is classified into four categories, namely, no, slight, moderate, and extensive, as shown in Fig. 8. It can be confirmed that, liquefaction-induced damage was not seen on the north side of the old coastline as of 1964, but was widely developed in the area reclaimed after that year. The areas that had experienced liquefaction in the 1987 Chiba-ken Toho-oki Earthquake did re-liquefy. The degree of damage, however, varied from place to place within the reclaimed areas. In particular, some of the reclaimed zone

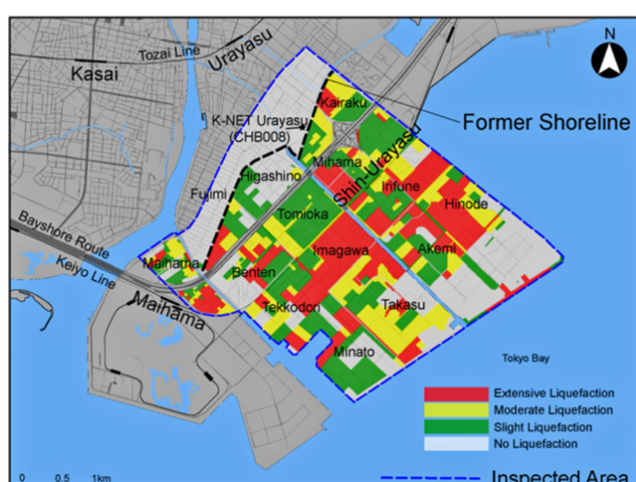

Fig. 8. Map showing liquefied area.

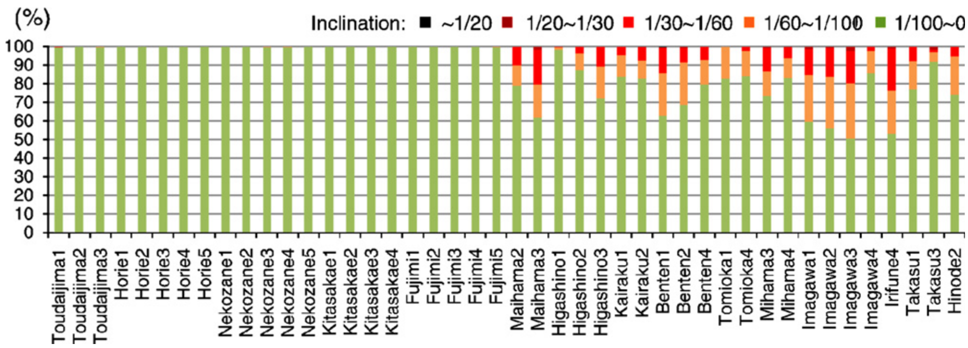

Fig. 9. Distribution of inclination angles district by district.

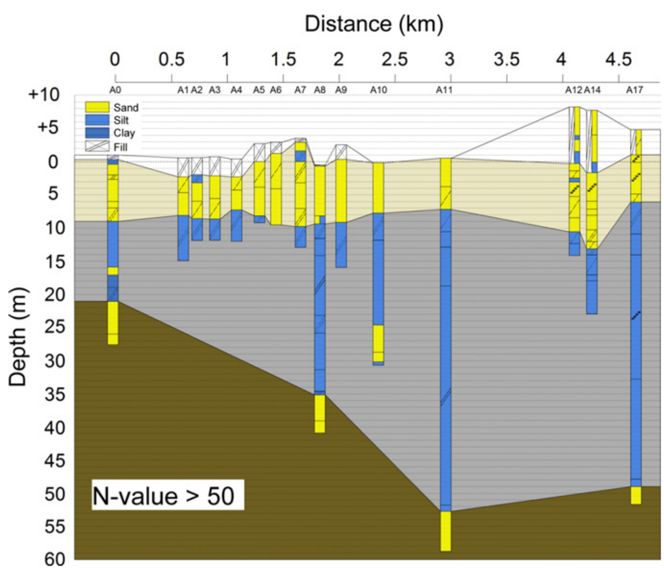

Fig. 10. Geological section along A–A' line.

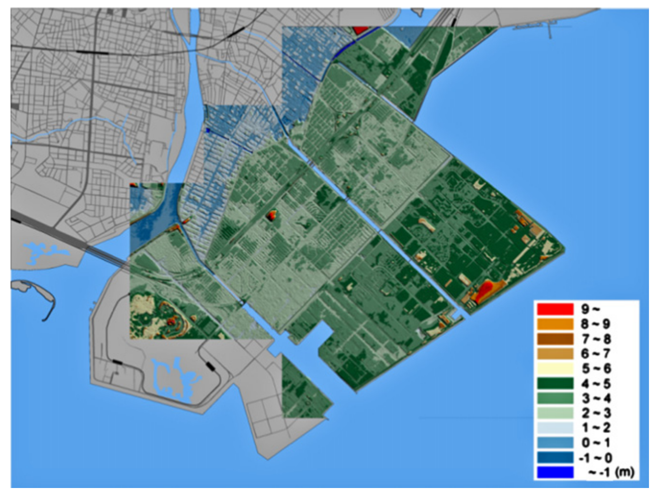

Fig. 11. Map showing elevation of Urayasu City before main shock.

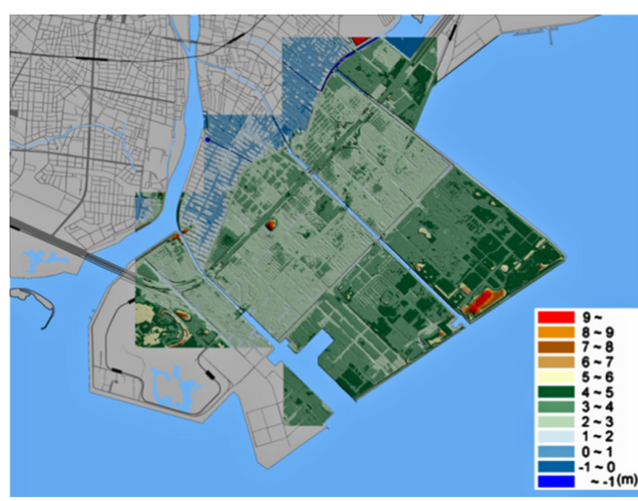

Fig. 12. Map showing elevation of Urayasu City after main shock.

escaped liquefaction damage completely, probably due to ground treatment, including remedial measures against soil liquefaction.

Fig. 9 shows the distribution of the inclination angles of the residential houses supported on spread foundations with respect to residential districts, based on the survey conducted by the Urayasu City Government. The figure shows that houses located on the non-liquefied north side of the old coastline had no damage, while those located in the reclaimed area suffered extensive damage. In particular, about 1/3–1/2 of the houses in the residential areas of Maihama 3-chome, Benten 1-chome, Imagawa 1 to 3-chome, and Irifune 4-chome tilted more than 1/100. These areas are classified in the category of extensive damage in Fig. 8.

2.3. Ground structure and liquefaction damage in Urayasu City

Fig. 10 is the cross section of the ground in Urayasu City along the A–A' survey line in Fig. 7. Fig. 11 shows the elevation based on a digital elevation model with 2-x-2-m data spacing that was determined with an airborne scanning laser survey made before the earthquake (December 2006) (Geospatial Information Authority of Japan). The elevation is 0–2 m north of the old coastline of 1964, 2–4 m between the 1964 coastline and the 1971 coastline to the south, and 3–7 m in land reclaimed in or after 1979. The elevation is especially high in a park near a coastal levee in Akemi. Fig. 10 shows that the surficial deposits down to 10 m are mostly sand with earth fill in some areas. The

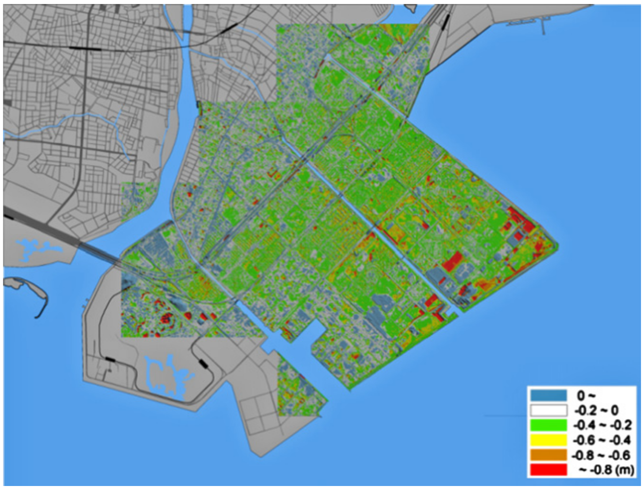

Fig. 13. Map showing ground subsidence in Urayasu City due to main shock.

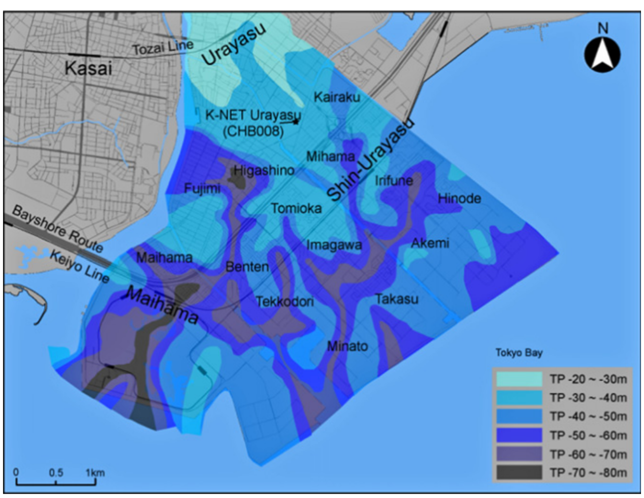

Fig. 14. Map showing thickness of alluvial soil in Urayasu City.

N-value is very small at 10 or lower in most places. Underlying below are deep silt and cohesive soil layers, with N-values of mostly 0–3. An airborne scanning laser survey was also conducted after the earthquake (April 2011). Fig. 12 presents the elevation based on the survey after the earthquake, while Fig. 13 shows the ground subsidence estimated from the difference between the elevation obtained before and after the earthquake. The ground in the liquefied area after the earthquake has settled 0.2–0.4 m on the average, with smaller settlements on the roads. The value of the subsidence reached 0.6–0.8 m in some areas.

Fig. 14 shows the depth distribution of the soft sediments (Urayasu City: Geographical and geological features of Urayasu City, 2011). Buried valleys, about 60 m deep, exist directly below the Minato, Imagawa, Akemi and Irifune areas, causing complicated changes in the thickness of the soft ground in those areas. A comparison between Figs. 10 and 14 shows that the depth to a stiff deposit, with N-values larger than 50, increases toward the sea (in the southeast direction), i.e., from 20 m near the old coastline on the north side to 50 m in the area closest to the sea. By comparison, along the northeast to southwest line, which is perpendicular to the A–A' line, the depth becomes greater in the southwest direction.

Fig. 15 presents the grain size distribution curves of the sand boil samples collected at the locations shown in Fig. 7. Each sample has a high fine-grain content ratio of 15–70 percent. Those fine grains are believed to be non-plastic fine sand or silty sand, which correspond to the composition of the sand layer in reclaimed land up to 10 m below the sea level. This suggests that the reclaimed sand layer might have liquefied at the time of the earthquake.

Fig. 16 presents depth distributions of the N-value of the earth filling or the sand layers at each area of Urayasu in gray. The average is shown in black. The data were obtained from the Chiba Prefectural Government and the authors' own survey (Chiba Prefectural Environmental Research Center, 2011). For the Akemi-Hinode area, separate graphs were given for the northwestern and

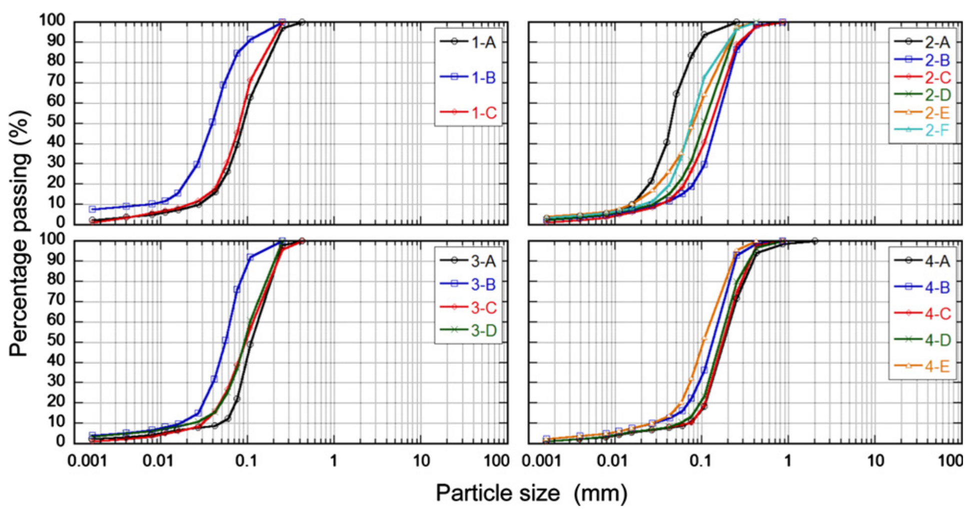

Fig. 15. Grain size distribution curves of boiled sand.

southeastern districts, because the extent of the damage was distinctively different between them. It can be seen in the figure that the *N*-value in the sand layer was extremely small in Tomioka, Imagawa and Akemi-Hinode (northwest), but large in the neighborhood of Urayasu Station, which is not reclaimed land, and in Akemi-Hinode (southeast), which is reclaimed land, but which is the highest in elevation. The thickness of the earth filling and the sand layers was different from place to place, with the largest values in Maihama, Mihama-Irifune, Takasu and Akemi-Hinode.

A comparison of these findings with liquefaction damage suggests the following:

- On the land side of the old coastline of 1964 or before, no liquefaction was observed, even though the elevation is low, and thus, the groundwater level is shallow. In addition, the *N*-value is higher in this area than in recently reclaimed land where liquefaction occurred. These facts suggest the possibility that the "aging effect" of the soil may have worked in mitigating the liquefaction.
- In the Akemi-Hinode area (southeast), the *N*-value is relatively high and the liquefaction damage was minor. It could be surmised that differences in the reclamation materials and in the method of reclamation may have affected the degree of damage. Furthermore, the elevation of the area is rather high, indicating the possibility that differences in elevation may also have affected the extent of the damage. This may be partly because the groundwater level becomes lower with an increasing elevation and partly because the overburden pressure in the fills becomes larger, accelerating the compression of the silty sand layer below the groundwater table.
- A comparison of Figs. 8 and 14 shows that major liquefaction damage tended to occur just above or near buried valleys. Therefore, it is likely that differences in the ground surface response due to differences in the thickness of the alluvial deposits could have affected the occurrence and the extent of the liquefaction.

Fig. 17 shows the distribution of the inclination angles of the residential houses with respect to ground subsidence. The figure apparently shows that the inclination angles tend to increase with an increasing liquefaction-induced ground settlement.

2.4. Liquefaction damage in Urayasu City and liquefaction prediction

Fig. 18 shows the results of a liquefaction evaluation made with a method specified in the Architectural Institute of Japan (2001), using the average *N*-value for each area (Fig. 16), a peak ground acceleration of 2.0 m/s^2 and a magnitude of 9.0. The groundwater level is set at the average for each area, and the fines content was set at three different levels—15%, 25% and 35%.

The *FL*-value (safety factor against liquefaction) came to 1 or more at most depths in the neighborhood of Urayasu Station, where no liquefaction damage was observed, and in the Akemi-Hinode (southeast) area, where only minor damage was seen. In other places, however, the *FL*-value was estimated to be lower than 1. Particularly in Mihama-Irifune, Takasu and Akemi-Hinode (northwest), there are sequences of layers with an *FL*-value lower than 1 until the depth of nearly 20 m. These results agree with the observed damage.

Table 1 presents a comparison of the average figure of estimated ground settlement, based on the *N*-value distribution in each area of Fig. 16 (calculation made under the AIJ guidelines), and the observed ground settlement. Since the fine-grain content ratio was not clear in many areas, estimates were made for 15%, 25% and 35%.

With a fines content of 25%, the estimated settlement was 6 cm near Urayasu Station and 11 cm in Akemi-Hinode (southeast). In other areas where the liquefaction was severe, however, the estimate was 16 to 33 cm, with the highest figure being for Akemi-Hinode (northwest). These estimates were generally in agreement with the tendency

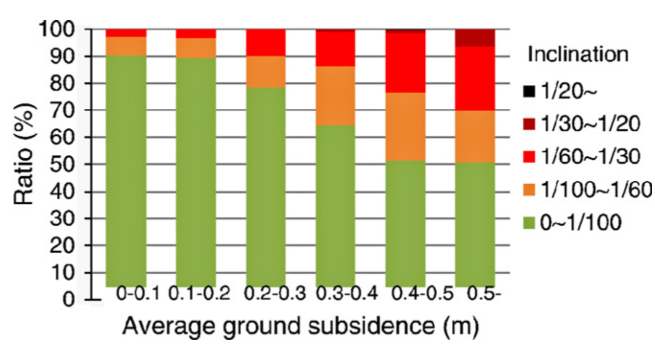

Fig. 17. Distribution of inclination angles of residential houses with respect to liquefaction-induced ground subsidence.

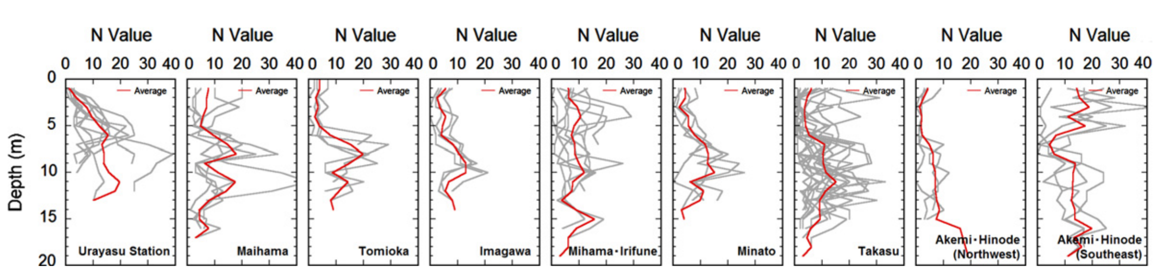

Fig. 16. Distribution of *N*-value with depth at selected districts in Urayasu City.

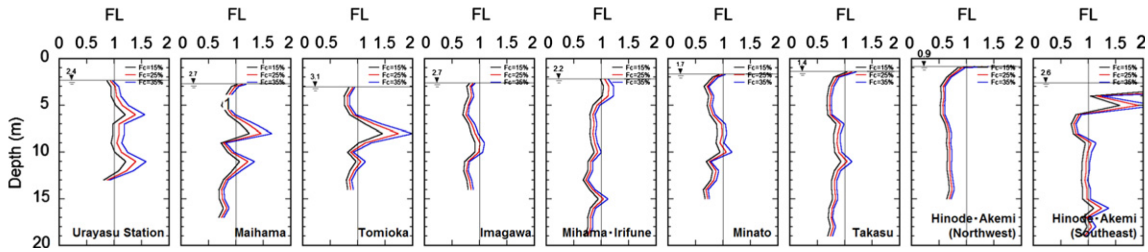

Fig. 18. Distribution of factor of safety against liquefaction with depth at selected districts in Urayasu City.

Table 1
Estimated and observed ground subsidence.

	Estimated (mm)			Observed (mm)		
	Fc=15% Av.	Fc=25% Av.	Fc=35% Av.	Max.	Av.	Min.
Neighborhood of Urayasu Station (Nekozane, Todaijima, Kitasakae)	90	60	50	0	0	0
Maihama	250	180	140	–	–	–
Tomioka	180	130	100	300	260	150
Imagawa	230	160	120	500	220	50
Mihama, Irifune	320	230	180	450	190	70
Minato	260	190	150	600	220	50
Takasu	380	280	230	500	230	20
Akemi, Hinode (Northwest area)	440	330	270	650	320	30
Akemi, Hinode (Southeast area)	170	110	90	150	80	20

seen in the actual figures. Even though a review is necessary, after clarifying the fines content for each area and each depth, the current design guidelines were able to predict, with a reasonable degree of accuracy, the possibility of liquefaction and the degree of damage.

3. Liquefaction damage in Tone River Region

Soil liquefaction occurred around the basin of the Tone River, as shown in Fig. 19 (Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transportation and Tourism, 2011). Houses suffered damage due to liquefaction in Kuki City and Satte City, Saitama Prefecture, and in various places in Chiba and Ibaraki Prefectures.

3.1. Damage in Katori City (Sawara area), Chiba Prefecture

Waterways leading to the Tone River crisscross the Sawara area of Katori City. A comparison with a 1955 map shows that much of the area and its waterways used to be marshes and river channels. Liquefaction damage was particularly conspicuous in the reclaimed land, including land along the waterways. The settlement and the tilting of buildings on spread foundations, the settlement of the ground adjacent to pile-supported buildings, the uplift of buried structures, and road surface irregularities and slumps were observed in many places. Along waterways, liquefaction-induced lateral spreading occurred, and the following damage was also observed:

Fig. 19. Map showing liquefied areas along the Tone River (Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transportation and Tourism, 2011).

- Due to liquefaction-induced lateral spreading, the stream became narrow and the riverbed lifted (Photo 8). The ground behind the embankment also settled greatly

Photo 8. Lateral ground spreading towards river.

Photo 9. House damaged by lateral spreading.

and shifted horizontally, causing damage to a bridge across the stream.

- Houses and other structures near the embankment had their foundations tilted, as if pushed toward the stream, and some collapsed (Photo 9). Those, which collapsed, were generally old structures that lacked foundation rigidity. A gap of up to 50 cm emerged between the pile-supported buildings and the ground surrounding them.

3.2. Itako City (Hinode area), Ibaraki Prefecture

In the Hinode area of Itako City, extensive soil liquefaction occurred along with numerous sand boils, having caused the settlement and the tilting of buildings on spread foundations as well as utility poles, ground settlement around buildings supported by pile foundations (Photo 10), the uplift of buried structures and the dents and bumps of roads and sidewalks (Photo 11). Water supply and sewer systems were both blocked in the entire Hinode area immediately after the earthquake. Liquefaction damage was larger in the southern part of the area, through which the Hitachi-Tone River, a tributary of the Tone River flowing out of Lake Kasumigaura, runs. The degree of ground settlement was accordingly larger in the

Photo 10. Ground settlement around building.

Photo 11. Damage to sidewalk.

south, at 40–50 cm near the Itako Sewage Treatment Plant, than in the north at 10 cm or less.

A look at a 1955 map reveals that the Hinode area corresponds to the former Uchinasakaura reclamation land (project: 1934–1949). Wakamatsu (1991) reported a past liquefaction case history in the Hinode area during the Chibaken Toho-oki Earthquake of 1987. In the March earthquake, liquefaction occurred on a far greater scale and affected much wider areas, causing more serious damage to houses and lifelines, including water and sewer systems.

3.3. Kamisu City, Ibaraki Prefecture

The March earthquake severely damaged a water purification plant in Kamisu City's Wanigawa area (partly in Kashima City), breaking water pipes leading to water distribution facilities and cutting off the water supply to neighboring communities.

At the Wanigawa Purification Plant, liquefaction-induced ground settlement of up to about 50 cm and the uplift of a public utility duct by up to 50 cm (Photo 12) occurred. This resulted in a gap of up to 40 cm in the vertical direction between a pile-supported building and the duct, which severed some of the wiring inside the duct. Horizontal gaps of up to 15 cm were also created at many joints of the duct,

Photo 12. Uplift of buried conduit.

Photo 13. Titled building on edge of fill.

leading large quantities of sand to flow into the duct, which added to the scale of ground settlement. Liquefaction-induced lateral spreading also occurred toward a regulation reservoir at the center of the site, exacerbating ground settlement, raising the water level in the reservoir and inundating roads in the plant.

In the Fukashiba and Horiwari areas, liquefaction also caused the settlement and the tilting of buildings on spread foundations (Photo 13), the settlement of the ground adjacent to buildings supported by pile foundations, the uplift of buried structures and bumps and dents in roads and sidewalks. Sand boils in Fukashiba measured up to 50 cm in thickness in some places. The outdoor units of air conditioners were buried in sand boils. When several structures stood closely together, they tended to tilt toward each other (toward the center), probably due to structure-soil-structure interaction (Photo 14). Several houses located at the end of the filled land tilted in the direction of lower ground (outside the land) as the earthfill collapsed due to liquefaction (Photo 13). The northern part of the Horiwari area suffered serious damage—an underground drain was uplifted and houses standing along a street settled by up to 50 cm vis-à-vis the road surface or adjacent houses, but the southern part suffered only minor damage. Puddles of water

Photo 14. Larger settlement occurring in middle.

formed in all of these areas experiencing liquefaction, indicating that the groundwater level was extremely shallow.

A 1955 map of the Kasumigaura area shows that the Wanigawa area and the northern part of the Horiwari area correspond to the Wanigawa reclamation land (project: 1928–1942). The reclaimed land was later developed into residential land, where the March temblor triggered liquefaction. Meanwhile, the southern part of the Horiwari area, which suffered only minor damage from liquefaction, was used for conifer forests. In the Fukashiba area, residential districts that were once used as rice paddies suffered major damage, while land plots along an old main road and old communities suffered little damage. A stone monument in Fukashiba area shows that ‘‘soil treatment including dredging’’ was carried out in 1957–1959 to improve the farmland. Since extensive soil liquefaction occurred in March in this area, the treatment might have had adverse effects on the soil liquefaction susceptibility.

4. Tohoku region

4.1. Lowland of Sendai City

i) **K-NET Sendai (MYG013)**

Sand boiling occurred in the neighborhood of K-NET Sendai in Nigatake, Miyagino Ward, Sendai City (MYG013, at Miyagino Fire Station), where ground adjacent to pile-supported buildings settled by about 3 cm. Most of the settlements reportedly took place just after the main shock. No structural damage was observed to the buildings themselves. At the K-NET Sendai station, the peak ground accelerations in the NS and EW directions during the main shock were 15.15 m/s^2 and 9.77 m/s^2, respectively

Figs. 20 and 21 present the acceleration time histories and the running spectra of the main shock, normalized at the spectral peak of each interval, respectively. Fig. 20 shows spiky waves at around 90 s, indicating the possibility of the cyclic mobility of sand due to liquefaction. Fig. 21 shows that the peak period was elongated from 0.6 s to about 1 s at around 90 s. These amounts mean

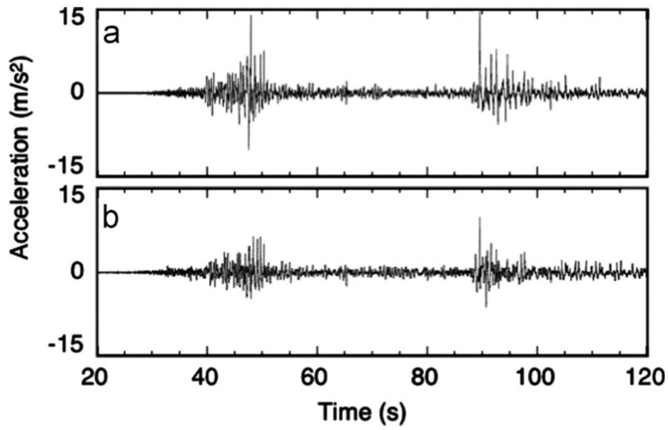

Fig. 20. Acceleration time histories at K-NET Sendai during main shock.

Photo 15. Tilted building.

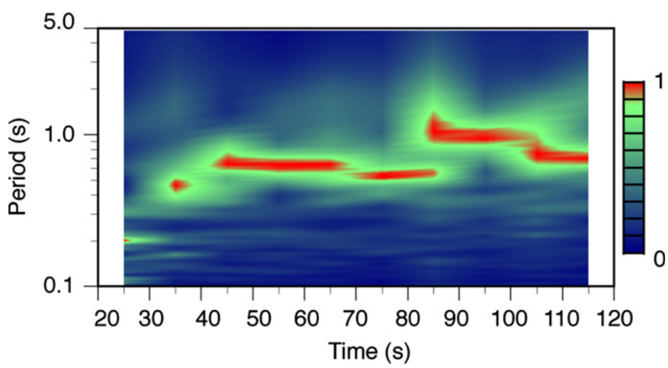

Fig. 21. Normalized running spectra in Sendai.

Photo 16. Settlement of pile-supported building.

that excess pore water pressure at some depth in the ground may have reached the peak around this time or may have become equal to the initial effective stress, triggering soil liquefaction. However, the peak period of 1.0 s continued only for about 15 s and then it decreased. This indicates that liquefaction may have been incomplete or that the increased excess pore water pressure may have dissipated, probably because the layer with the increased water pressure was thin or because the permeability of the ground was high.

ii) **Pile damage in Sendai City**

In the western part of the Oroshimachi-Higashi area, soil liquefaction induced sand boiling, the settlement of the ground adjacent to structures supported by a pile foundation, the uplift of buried structures, and bumps and dents in roads and sidewalks. The settlement of the ground surrounding the pile-supported buildings measured about 10–20 cm. At least two buildings, apparently supported by pile foundations, tilted considerably. A similar pattern of building damage, associated with pile failure involving soil liquefaction, was observed in the Fukumuro area. Photo 15 shows a 14-story, steel-reinforced condominium complex with a pile foundation (built in 1976), which consisted of two buildings connected with expansion joints in an *L*-form on the plan, with the bottom of the letter L facing south. It has been reported that the complex's nonstructural walls suffered shear fractures in the 1978 Miyagiken-oki Earthquake. In the March earthquake, the southern building tilted southward by about 1 degree as its foundation on the south side settled (Photo 16). There were large cracks in the nonstructural walls of various parts of the building, but no significant damage was observed in the major structural components. The ground settlements around the neighboring buildings were about 10 cm.

4.2. Hilly land of Sendai City

Many residential areas in Sendai City were developed by the cut and fill method with thicknesses varying from almost zero to about 30 m (Fukkenn Gijutu Consultant Co., Ltd., 2008).

i) **Oritate 5-chome in Aoba Ward, Sendai City**

The Oritate housing complex was built in the latter half of the 1960s, and put for sale in the first half of the 1970s. No geotechnical problems were reported at the complex after the 1978 Miyagiken-oki Earthquake (the

Fig. 22. Map showing damaged area in Oritate 5-chome.

Photo 17. Damage to retaining wall.

Architectural Institute of Japan, 1980; and the Tohoku Branch of Japan Society of Civil Engineering, 1980).

Fig. 22 shows a damaged area in Oritate 5-chome, where many retaining walls failed. At the lower part of a slope (P1 in Fig. 22), retaining walls collapsed as if they had been pushed out by backfill soil (Photo 17). Above that point, at P2, the ground under a retaining wall was raised, as Photo 18 shows. It is believed that the earth fill had moved toward the street, exerting a compressive force.

Photo 18. Ground heaving beneath retaining wall.

Photo 19. Damage to wooden house.

Near these two locations were many retaining walls made up of more than one tier. In some cases, the upper part of the wall had apparently been built more recently than the lower part, indicating that some repairs may have been done. At a somewhat high point on the slope (P3), there were major cracks in a residential land plot. At a high part of the slope, there were also retaining walls with tensile cracks. This means that a tensile force was applied to the ground at these points. Fig. 22 shows the points of tension and compression found from these examples, suggesting that a landslide occurred in the hatched part of the figure. A comparison with an old topographical map (around 1964) shows that the landslide area roughly corresponds to a valley in the old landscape. The March earthquake apparently led the entire earth and sand, used to fill up the valley, to shift. In fact, a road that ran straight before the earthquake was curved where the landslide occurred (P4).

A house that straddles the landslide area and a cut slope were broken around the boundary (P5). Severe damage to houses was concentrated at the foot of the landslide area, represented by the shaded section in Fig. 22 (Photo 19). The ground in the area spread from the mountain side (left) to the valley side (right), causing the damage to houses. The damaged strip footing foundation had no reinforcing steel. Damage was greater at the end of the landslide block because ground deformation became greater in both horizontal and vertical directions.

ii) **Aoyama 2-chome in Taihaku Ward, Sendai City**

The Aoyama housing complex was built in the latter half of the 1960s. Numerous cracks, bulges and collapses of retaining walls were observed during the 1978 Miyagiken-oiki Earthquake (Architectural Institute of Japan, 1980). According to residents' accounts, some houses whose foundations had broken in the 1978 earthquake had the same misfortune during the 2011 main shock.

Fig. 23 presents the damaged area in Aoyama 2-chome. A major crack formed in a housing lot at the upper part of the slope (P1 in Fig. 23). The crack was as deep as 70 cm. Closer to the valley at P2, the retaining wall shifted about 1 m to the valley side, causing the ground to sink and leaving a void below the foundation, as seen in Photo 20. At the lower part of the slope, a residential land plot was destroyed as if pushed out, as seen in Photo 21 (P3 in Fig. 23). Fig. 23 shows the points of tension and compression found from these examples, which outline the landslide area shaded in the figure. Comparing the area, with that on an old topographical map (around 1964), shows that the area roughly coincides with an earth cliff in the old landscape. The landslide occurred in the residential land developed by widening the earth fill along the cliff. Residents said that the groundwater level in the neighborhood is generally extremely shallow, about 1 m in depth, which is considered to have been a factor leading to the landslide.

Some buildings at the lower part of the landslide block suffered severe damage as a whole, as seen in Photo 22 (P4 in Fig. 23). In Aoyama 2-chome, the ground shift was large in scale in the upper part of the landslide block, severely damaging many detached houses there. Some of the collapsed houses had been retrofitted and their superstructures had been reinforced against earthquakes. This fact suggests the need to make a comprehensive judgment on anti-seismic reinforcements, considering not just superstructures, but also foundations and land plots.

Residents said the ground cracks and bulges of retaining walls were initially created by the main shock of March 11 and became worse with each aftershock. The aftershock of April 7, in particular, exacerbated ground deformations and destroyed foundations, suggesting the possibility of the progressive failure of the ground.

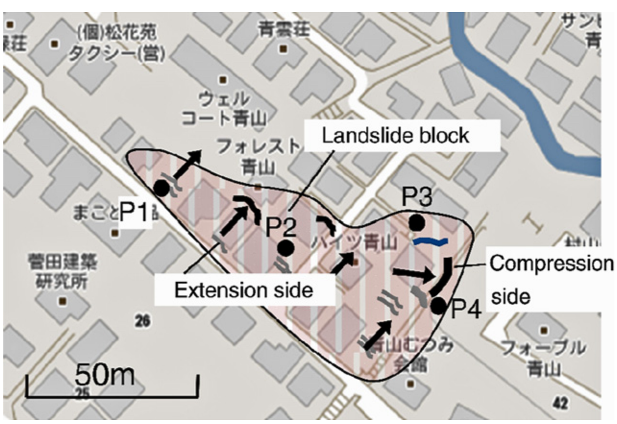

Fig. 23. Map showing damaged area in Aoyama 2-chome.

Photo 21. Failure of reclaimed fill.

Photo 20. Damage to foundation of wooden house.

Photo 22. Damage to wooden house.

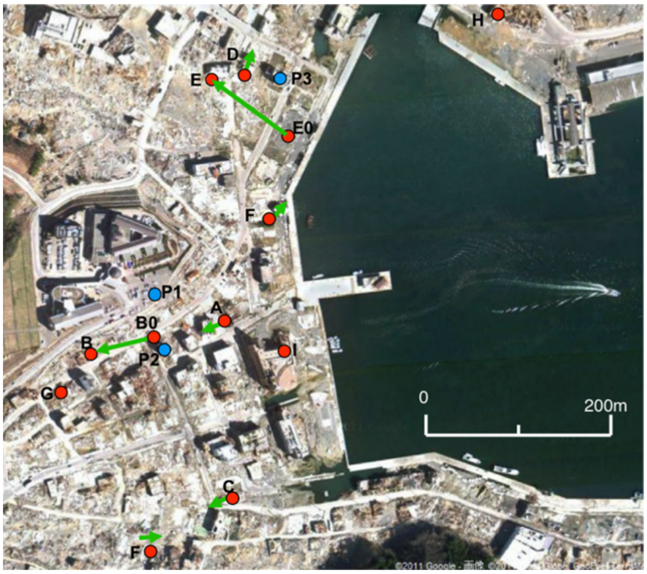

Fig. 24. Aerial photo of Onagawa taken after main shock, after Google Earth.

Photo 23. View of Onagawa.

4.3. Tsunami-induced damage to structures along the Sanriku Coast

i) **Onagawa, Miyagi Prefecture**

Fig. 24 is an aerial photo (by Google Earth) of Onagawa Town. Photos 23 and 24, taken from the parking lot of Onagawa Town Hospital (P1 in Fig. 24), show the townscape after the tsunami of March 11. The tsunami surged up to the first floor of the hospital, which stands on a hill 16 m above sea level. The inundation height in Onagawa was about 17 m.

At Point A, a four-story, steel-frame building, supported by a pile foundation, was swept toward the mountain side by about 10 m and toppled sideways (Photo 25). A parking lot between the building's original location and where it ended up had insignificant damage, except for a crack likely made when the building was washed away. This shows that the building apparently floated by the tsunami's force, was carried away and then toppled. The foundation of the building had pile caps, each supported by two or three piles (Photo 26). The toppled building had one pre-stressed concrete (PC) pile with a diameter of 300 mm hanging from its foundation. All the other piles had broken away at their connections with the pile caps. The joints were made of filling concrete, which was weak. Most of

Photo 24. View of Onagawa.

Photo 25. Toppled Building A.

the concrete crumbled and was washed away, with reinforcing steel alone remaining. The pile head joints were possibly damaged by the earthquake and then fractured by the ensuing tsunami.

At Point B, a four-story, reinforced concrete building with a pile foundation lay on its side (Photo 27). The building used to stand at Point B0, from which it was swept toward the mountain side by about 70 m. As Photo 27 shows, a PC pile with a diameter of 300 mm was hanging from the pile cap. The pile head barely remained connected with the cap, by reinforced steel, but the rest of the pile suffered comparatively minor damage. Most of the other piles were found at Point B0, either fractured at their heads or head joints, or pulled from the ground with damage at or near their heads (Photo 28). The state of destruction of these piles suggests that bending and tensile forces might have been a major cause of the failure. The ground around a neighboring five-story, reinforced concrete building (P2) settled, indicating the occurrence of soil liquefaction. Therefore, it is conceivable that, when soil liquefaction had lowered the shear strength of the ground, the horizontal and buoyant forces acting on the building by the tsunami might have pulled the piles out of the ground or caused complete failure at the pile heads.

At Point C, a two-story, reinforced concrete building with a pile foundation (that appeared to be a refrigerated warehouse) toppled sideways (Photo 29). This building was also swept by about 7 m, from the coast to the landside, before being toppled over sideways. It apparently crossed over a wall, about 1 m in height, along its way, suggesting that it floated up by more than

1 m while being washed away. As the pile caps of this building, each connected to four to five piles, were extremely fragile, all the piles were ruptured at or near the joints.

At Point D, a two-story, reinforced concrete building with a pile foundation (police box) was tipped over sideways (Photo 30). This building fell down almost perpendicular to the sea, probably due to a collision with a floating vessel or the complex flow patterns of the tsunami. Some piles were broken at their upper parts and others at their joints with pile caps. Photo 31 shows the ground adjacent to a neighboring building (on the sea side, at P3, or seen in the background of Photo 30). The adjacent ground apparently settled, indicating that soil liquefaction had occurred in the neighborhood. This neighboring building, incidentally, did not shift or tilt. The reason is probably because it was built in recent years, with a seismic design for its pile foundation.

Point I is the site of the Marine Pal Onagawa (three-story, reinforced concrete building founded on piles), a tourist facility on the coast (Photo 32). Facing the sea, this facility was apparently hit directly by the tsunami and the soil around the building was washed away. There was, however, no damage to the building, probably because it had an aspect (height/width) ratio smaller than those of the toppled buildings and was built more recently (in 1993) with a more up-to-date seismic design for pile foundations.

ii) **Rikuzentakata, Iwate Prefecture**

Photo 26. Pile of toppled Building A.

Photo 27. RC Building B carried 70 m away and toppled.

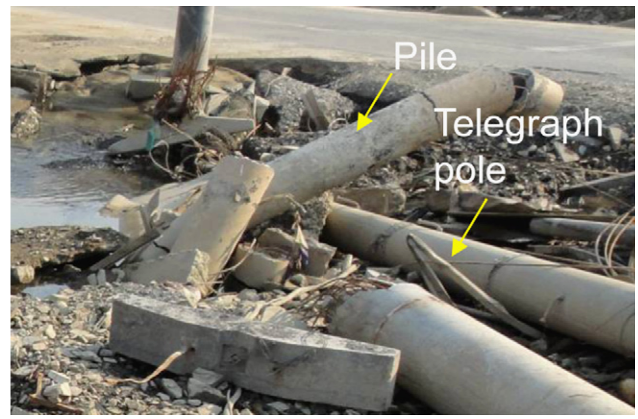

Photo 28. Piles failed by bending and pull-out forces.

Photo 29. Overturned Building C.

Photo 30. Toppled Building D.

Photo 31. Ground settlement around nearby building.

Photo 32. Building I.

Fig. 25. Aerial photo of Rikuzen-takata taken after main shock, after Google Earth.

Photo 33. Building A.

Photo 34. Scour around Building A.

Photo 35. Overturned Building B.

Fig. 25 is an aerial photo (by Google Earth) of Rikuzentakata City after the March 11 earthquake and tsunami. Iwate Prefectural Takata Hospital, shown in Photo 33, is located at Point A in Fig. 25. Tsunami waters reached the hospital's fourth floor. The inundation height was 14–15 m. As Photo 34 shows, some footings were exposed as the tsunami washed soil away, but the building escaped settlement and tilt. There was

Photo 36. Pile cap of Building B.

damage apparently caused when some drifting object hit, but damage to the structure itself was minor.

At Point B, a two-story, reinforced concrete building, which appeared to be a house, lay upside down (Photo 35). It was supported by piles, but with fragile connections to the pile caps, and thus, there were traces of piles in one of the pile caps (Photo 36). The joints between the caps and the piles were fragile. The building was surrounded by debris, and its original location is unknown. At Point C, there was also a two-story reinforced concrete building that had similarly turned over. Its original location was not available either. At Point D, a two-story, reinforced concrete building on a spread foundation was toppled over sideways, from the sea side to the mountain side. At Point E, in contrast, another two-story, reinforced concrete building was toppled from the mountain side to the sea side.

5. Conclusions

Field surveys on building damage associated with geotechnical problems in the 2011 Tohoku Pacific Earthquake have revealed the following:

1) Liquefaction generally occurred around Tokyo Bay and in the basin of the Tone River in land areas reclaimed in relatively recent years. In some places, liquefaction caused severe sand boils and ground settlement of up to 50 cm, leading to damage such as the tilt and the settlement of wooden and reinforced concrete buildings on spread foundations, the uplift of buried structures and the slumps of roads. Liquefaction also caused a major gap between pile-supported buildings and the surrounding ground, but no structural damage was observed in superstructures. Buildings on spread foundations having high rigidity, such as mat foundations, did not suffer structural damage to their superstructures, even when they settled or tilted.
2) The degree of liquefaction differed from place to place, even within the same city, and may have depended on such factors as the thickness of the reclaimed fill or the alluvial deposit, the elevation or the groundwater table, and the presence of ground improvements, as well as the reclamation year, and the method and the material used for the reclamation.
3) Some of the collected sand boil samples had high fines contents, indicating that the finely grained sands had liquefied.
4) The currently available liquefaction evaluation procedure appeared to have performed well in predicting the occurrence of soil liquefaction as well as the degree of resulting ground settlements. However, there is a need to obtain more detailed data on the ground and to scrutinize the adequacy of the above methods.
5) In Sendai City and the Tokyo Bay area, several pile-supported buildings suffered tilt and settlement, indicating damage to their pile foundations, mostly accompanied by sand boils and nearby liquefaction-induced ground settlements.
6) Damage to houses in the Oritate and Aoyama areas of Sendai City was not caused simply by the collapse of retaining walls, but involved earth fill slides that destroyed their plots of land. Piecemeal work to reinforce retaining walls may fail to prevent future damage to residential land; large-scale landslide prevention measures are necessary as a public works project.
7) In Onagawa and Rikuzentakata, where the tsunami was extremely high, many two- to three-story, reinforced concrete buildings toppled sideways or overturned, even though they were considered to have been rather stable against horizontal forces, due to their relatively small aspect ratios. In addition to the pressure of the tsunami, that far surpassed their heights, the force of the water's buoyancy is believed to have contributed to their overturning.
8) In Onagawa and Rikuzentakata, pile foundations were destroyed, leading steel buildings and reinforced concrete buildings to be swept away and toppled. Most of the pile destruction occurred at the pile cap-pile joints or near the pile heads. The toppled pile-supported buildings were rather old, and apparently were not built with a seismic design. For this reason, the cap-pile joints, or the piles themselves, suffered a certain extent of damage from the earthquake, becoming unable to withstand the tsunami's wave pressure and buoyancy force.
9) In Onagawa, some of pre-stressed concrete piles of two toppled buildings were pulled away from the ground despite damage to their head joints. This was partly due to the tsunami's horizontal and buoyancy forces applied to the piles when the ground liquefied and to the reduction in shear strength. Some of the piles, retaining a sufficient amount of tensile strength, were pulled off the ground despite the damage to their heads.
10) Large-scale, newly built structures, such as Marine Pal Onagawa, did not tilt or shift despite being directly hit by the tsunami. No structural damage was observed in the buildings, including their foundations. This is probably because those buildings had aspect ratios

smaller than those of the toppled buildings and because they were built using a more up-to-date seismic design for pile foundations.

Acknowledgments

This survey was conducted jointly with Dr. Eisuke Nishikawa, a researcher at the Tokyo Institute of Technology's Global COE Program, Messrs. Youhao Zhou, Kodai Watanabe, Yoshiaki Ibaraki, Kei Inamura, Yuki Takeda, Yusuke Nakano and Kazushi Tohyama, graduate students of Tokyo Institute of Technology, Dr. Akio Abe of Tokyo Soil Research Co. and the GEER team from the United States (Profs. Ross Boulanger, Scott Ashford, Jonathan Stewart, Kyle Rollins and Steve Kramer and Dr. Jennifer L. Donahue). Research on the damage in Oritate 5-chome and Aoyama 2-chome was done jointly with Dr. Kazuhiro Hayashi of Kyoto University's Disaster Prevention Research Institute (JSPS research fellow), Dr. Kazuaki Hoki (DPRI, post doctoral research fellow), Dr. Chung Yulin (DPRI, JSPS fellowship program for foreign researchers), and Messrs. Sachi Furukawa, Mai Ito, Ryuta Enokida and Amane Kuriki, graduate students of Kyoto University. We greatly appreciate their support and cooperation.

References

Architectural Institute of Japan, 1980. Report of the 1978 Miyagiken-oki Earthquake. (in Japanese).

Architectural Institute of Japan, 2001. Recommendations for Design of Building Foundations. (in Japanese).

Architectural Institute of Japan, 2011. Preliminary reconnaissance report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake. (in Japanese).

Bureau of Port and Harbor, Tokyo Metropolitan Government, 2001. Geographical and Geological Features of Tokyo Port. (in Japanese).

Chibaken Kankyo Kenkyu Center, 2011. Soil liquefaction in Chiba Prefecture in the Tohoku Pacific earthquake, 〈http://www.wit.pref.chiba.lg.jp/_sui_chi/chishitu/touhoku/touhoku.html〉 (accessed 27.10.11).

Chiba Prefectural Environmental Research Center, 〈http://www.pref.chiba.lg.jp/suiho/chishitsu.html〉 (accessed 27.10.11).

Fukkenn Gijutu Consultant Co., Ltd, 2008. Map of developed residential sites.

Geospatial Information Authority of Japan, Digital elevation model with 2-x-2 m data spacing.

Kaizuka, S., 1993. Geographical and geological and features and water of Tokyo Bay, Tsukiji-shokan. (in Japanese).

Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transportation and Tourism, 2011. Investigation on soli liquefaction in Kanto region in the 2011 Tohoku Pacific earthquake. 〈http://www.ktr.mlit.go.jp/bousai/bousai00000061.html〉 (accessed 27.10.11).

Koto Ward, 2011. Damage in Koto Ward in the 2011 Tohoku Pacific earthquake, 〈http://www.city.koto.lg.jp/seikatsu/bosai/58976/58570.html〉 (accessed 27.10.11).

Ministry of Land, Infrastructure, Transportation and Tourism, 2011. Report on Great East Japan earthquake, 〈http://www.mlit.go.jp/common/000139083.pdf〉 (accessed 27.10.11).

National Research Institute for Earth Science and Disaster Prevention, 2011. Kyoshin Network K-NET, 〈http://www.k-net.bosai.go.jp/k-net/〉 (accessed 27.10.11).

Tohoku Branch of Japan Society of Civil Engineering, 1980. Report of the 1978 Miyagiken-oki earthquake. (in Japanese).

Tokimatsu, K., Tamura, S., Suzuki, H., Katsumata, K., 2011. Damage to soils in the 2011 Tohoku Pacific earthquake. Research Reports on Earthquake Engineering No. 118, 21–47.

Urayasu City: Project of reclaimed land, 〈http://www.city.urayasu.chiba.jp/menu2863.html〉 (accessed 27.10.11).

Urayasu City: Geographical and geological features of Urayasu City, 〈http://www.city.urayasu.chiba.jp/menu3185.html〉 (accessed 2011.10.27).

Wakamatsu, K., 1991. Maps for historic liquefaction sites in Japan. Tokai University Press, (in Japanese).